MINIMUM BIAS AND UNDERLYING EVENT STUDIES
AT ATLAS AND CMS

M. LEYTON

(on behalf of the ATLAS and CMS Collaborations)
Lawrence Berkeley National Laboratory, 1 Cyclotron Rd,
Berkeley CA 94720, USA

An overview of minimum bias and underlying event studies at the LHC with the ATLAS and CMS detectors is presented. Current uncertainties in the modeling of soft pp inelastic interactions at the LHC energy scale are discussed. Triggers used to select inelastic interactions at ATLAS and CMS are described and compared. A summary of some of the ongoing minimum bias and underlying event analyses by the ATLAS and CMS collaborations is given.

Minimum bias and underlying event properties have previously been studied over a wide range of energies. In particular, results from experiments at CERN and Fermilab have been used to tune the PYTHIA [1] and PHOJET [2] Monte Carlo event generators. However, due to uncertainties in the modeling of the energy dependence of soft inelastic interactions, these generators give widely varying predictions when extrapolated to LHC energies [3].

1   LHC, ATLAS & CMS

The Large Hadron Collider (LHC) [4] at CERN will collide protons at a center-of-mass energy of $\sqrt{s} = 14$ TeV. An initial physics run at 10 TeV is expected to start in October 2009. Peak luminosity for the 2009–2010 run will be $\mathcal{L} = 5 \times 10^{31}$ cm^{-2}s^{-1}, or about 1.8 interactions per bunch crossing. Total integrated luminosity during the first 100 days will be about 100 pb^{-1}.

ATLAS [5] and CMS [6] are 4π general-purpose detectors designed for high-luminosity studies at the LHC. Tracking detectors for both ATLAS and CMS cover a pseudorapidity range of $|\eta| < 2.5$. Both experiments have a multi-layer silicon tracker with pixels and strips. In addition, ATLAS has a transition radiation straw tracker. The ATLAS and CMS tracking chambers are immersed in a solenoidal magnetic field of 2 T and 4 T, respectively. Both detectors have electromagnetic calorimetry covering $|\eta| \lesssim 3.0$ and hadronic calorimetry covering $|\eta| \lesssim 5$.

2   Minimum Bias

'Minimum bias' events are usually associated with the non-single-diffractive (NSD) inelastic portion of the total cross section.[a] They are dominated by soft interactions, with low transverse momentum (p_T) and low particle multiplicity. Studies with minimum bias events are possible with very early data (1–10 pb^{-1}), ideally during low-luminosity running, when the number of pp collisions per bunch crossing is ≤ 1. At higher luminosities, minimum bias will be a major

---

[a]The total cross section (σ_{tot}) at the LHC can be written as a sum of elastic (σ_{elas}) and inelastic (σ_{inel}) components, with the inelastic part further sub-divided into single-diffractive (σ_{sd}), double-diffractive (σ_{dd}) and non-diffractive (σ_{nd}) components [3]. Central diffraction has been ignored.

background, with an average of 18 minimum bias interactions per bunch crossing at LHC design luminosity [7]. It is therefore very important to have an accurate model of minimum bias for all other high-p_T physics measurements.

A list of some of the important observables in minimum bias events, along with corresponding predictions by PYTHIA version 6.214 (ATLAS tune) and PHOJET version 1.12, is given here [3]:

- total cross section, σ_{tot}: 102–119 mb (17% difference);

- average charged particle multiplicity, $\langle n_{\text{ch}} \rangle$: 119–70 (30% difference);

- density of charged particles in the central region, $dN_{\text{ch}}/d\eta|_{\eta=0}$: 6.8–5.1 (30% difference);

- average transverse momentum, $\langle p_T \rangle$: 0.55–0.64 GeV/c (17% difference).

Measuring $dN_{\text{ch}}/d\eta$ (see section 2.2) at different LHC collision energies will be especially crucial for choosing between models since PYTHIA and PHOJET predict drastically different behaviors with different logarithmic dependencies [3]. The average p_T in the central region is also important since it is very sensitive to the tuning of Multiple Partonic Interactions (MPI) [8].

Because of the wide range in the predictions of these quantities, a first measurement to within 10% can discriminate between the different models.

2.1 Minimum bias trigger

A minimum bias trigger is intended to select inelastic collisions with as little bias as possible. Several types of minimum bias triggers have been implemented by ATLAS and CMS in order to cover various phases of LHC running [7,9].

A *random trigger* (with beam pickup) at Level-1 is ideal since it accepts all types of inelastic events equally with zero bias. However, random triggering is very inefficient at low luminosities ($\mathcal{L} < 10^{30}$ cm^{-2}s^{-1}) since the probability of an interaction during a bunch crossing is $< 1\%$. At higher trigger levels, signals in the tracking detectors can be used to suppress empty bunch crossings (noise events). This so-called *track trigger* selects events with a minimum number of silicon hits or reconstructed tracks or both. These two trigger strategies are often combined into a random-based track trigger [7].

CMS will also use their forward calorimeter (FCAL), located between $3.0 < |\eta| < 5.0$, as a minimum bias trigger by requiring a minimum number of towers with transverse energy (E_T) greater than some threshold. ATLAS will use the Minimum Bias Trigger Scintillators (MBTS), located between $2.1 < |\eta| < 3.8$, by requiring energy deposit above threshold in one or more counters. Various scenarios and thresholds have been studied by both collaborations [7,9].

A summary of the ATLAS and CMS minimum bias triggers discussed here is given in table 1. Trigger efficiencies are shown for the various physics processes. All but one of the triggers are highly efficient at selecting non-diffractive events. The diffractive events, however, have much lower trigger efficiencies since these events typically have a lower track multiplicity than non-diffractive events, especially in the central tracking region. It is important to note that neither ATLAS nor CMS have a pure NSD trigger. Model-dependent corrections are therefore needed to compare measured distributions to past experiments [7].

2.2 Measuring the pseudorapidity density

One of the first physics results from ATLAS and CMS will be the measurement of the pseudorapidity density of charged particles, $dN_{\text{ch}}/d\eta$, in minimum bias events at the LHC. This analysis has been prepared by both experiments using a full detector simulation [7, 10]. The ATLAS version uses the MBTS trigger to define a minimum bias event sample. A selected subset of

Table 1: Efficiencies of selected ATLAS and CMS minimum bias triggers for various physics processes simulated at $\sqrt{s} = 14$ TeV. An E_T-threshold of 1 GeV has been used in the CMS FCAL trigger study.

Experiment	Trigger	Non-diff.	Double-diff.	Single-diff.	Beam gas
ATLAS	Track (≥ 2 tracks)	100%	65%	57%	40%
	MBTS (2 hits anywhere)	100%	83%	69%	54%
	MBTS (1 hit on each side)	99%	54%	45%	40%
CMS	Track (≥ 1 track)	99%	69%	59%	−
	FCAL (1 tower on one side)	81%	15%	15%	−
	FCAL (1 tower on each side)	48%	1%	1%	−

fully reconstructed tracks are then counted and corrected back to MC generator level. Track and vertex reconstruction inefficiencies are taken into account. The CMS version uses a random trigger, thereby selecting inelastic events. Hits are counted in each layer of the pixel detector and a conversion function is used to map these hits into tracks in pseudorapidity. Corrections are applied for event selection and looping low-p_T tracks. Neither the ATLAS nor the CMS analysis corrects for bias imposed by the trigger.

Figure 1 shows the results of the two analyses, using events generated with PYTHIA at $\sqrt{s} = 14$ TeV. The generated $dN_{ch}/d\eta$ distributions for the minimum bias (ATLAS) and inelastic (CMS) event sample have been reconstructed. The inelastic sample used by CMS includes a greater fraction of single and double-diffractive events which lower the average track multiplicity in the central pseudorapidity region. A lower p_T range is accessible by CMS ($p_T > 30$ MeV/c, compared to $p_T > 150$ MeV/c for ATLAS) since no tracking or alignment is needed by the hit-counting method.
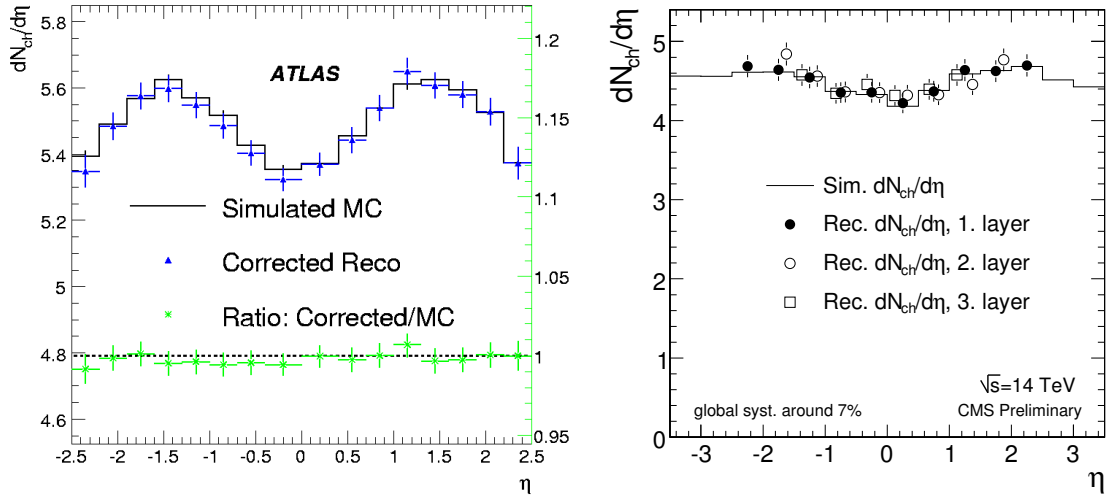

Figure 1: Results of simulated $dN_{ch}/d\eta$ analyses for the ATLAS minimum bias (*left*) and the CMS inelastic (*right*) event samples. Distributions have been integrated over $p_T > 150$ MeV/c (*left*) and $p_T > 30$ MeV/c (*right*).

The total estimated systematic uncertainty for both analyses is about 7%. The dominant source of uncertainty in the ATLAS analysis comes from mis-alignment of the tracker, but this is expected to decrease once the alignment from cosmic ray data is considered. The dominant sources of systematic uncertainty at CMS come from vertex bias and the hit-to-track conversion function.

3 Underlying Event

The Underlying Event (UE) is everything in the event except the hard scatter, including Initial State Radiation (ISR), Final State Radiation (FSR) and hadronization and beam remnants. From an experimental point of view, it is impossible to separate these two things; however, topological properties of the event can be used to define a set of physics observables which are sensitive to different aspects of the UE [11]. Studying the UE is important for understanding the evolution of QCD with collision energy as well as understanding the systematic corrections on many studies, from basic detector calibrations to physics analyses such as mass measurements.

Jet events are ideal for studying the UE. The approach by CDF is to look at observables in η-ϕ regions transverse (between $60°$ and $120°$ in azimuth) to the high-p_T objects (*leading jets*) [12]. Important observables include particle density, energy density and $\sum p_T$. The CDF analyses have shown that the density of particles in the UE in jet events is about a factor of two larger than in a typical minimum bias collision, a feature known as the 'pedestal effect' [11]. This tells us that the UE is not the same as minimum bias but that they are closely related.

As in the case of minimum bias, MC predictions at LHC energies are very uncertain, at the level of several hundred percent. For example, the particle density of events with leading jet $p_T > 10$ GeV/c is predicted to be between 13 and 29, a difference of over 200%. Uncertainties for underlying event predictions at the LHC come from the parton density functions, ISR/FSR gluon radiation, color flow and the modeling of MPI. Because of the wide range in LHC predictions, we can expect that 2009–2010 LHC data can already discriminate between models. Constraining of models and tuning of generators can follow shortly thereafter.

Measuring the underlying event: Figure 2 shows the results of a simulated underlying event study by CMS using 100 pb^{-1} of data [13]. Events were selected using a minimum bias trigger and an additional trigger on the p_T of the leading jet (20, 60 and 120 GeV/c). The plots show the MC generated curves for track multiplicity and $\sum p_T$ per dηdϕ region as a function of the charged jet p_T. The curve corresponding to the PYTHIA DWT tune has been reconstructed by the analysis for $p_T > 0.5$ GeV/c. With this much data, the reconstruction can resolve the various PYTHIA tunes quite well. A summary of the parameters for each of the various PYTHIA tunes considered in this study can be found in [11].
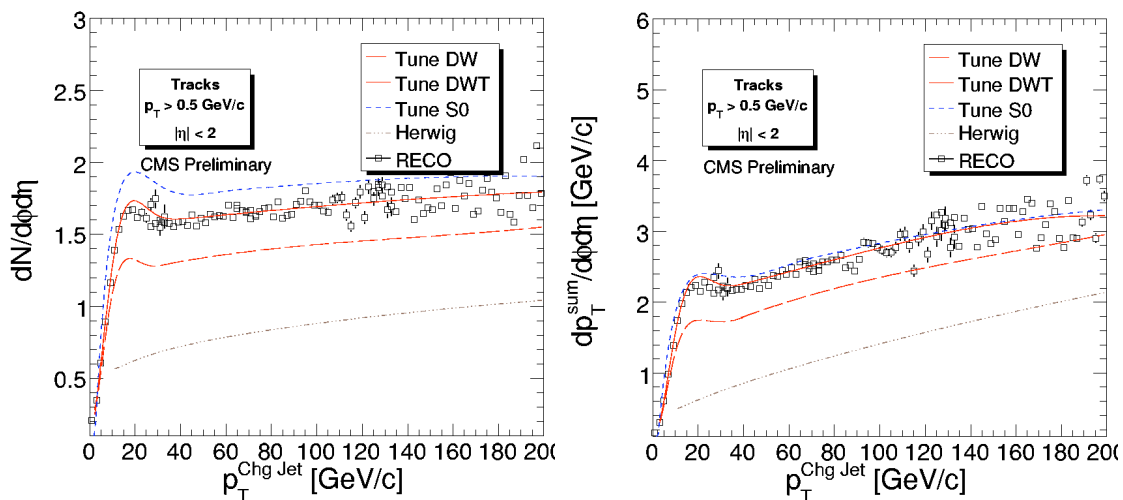

Figure 2: Results of a simulated CMS underlying event study. Corrected densities $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\mathrm{d}\phi$ (*left*) and $\mathrm{d}p_T^{\mathrm{sum}}/\mathrm{d}\eta\mathrm{d}\phi$ (*right*) for tracks with $p_T > 0.5$ GeV/c, as a function of the leading charged jet p_T, in the transverse region, for an integrated luminosity of 100 pb^{-1}.

4 Conclusion

The revised LHC program will include an initial physics run at $\sqrt{s} = 10$ TeV, followed by running at 14 TeV. This will allow measuring the energy dependence of Minimum Bias and Underlying Event, which is important for model tuning and constraining. Although current models of minimum bias and the underlying event diverge on LHC predictions, $1 < \int \mathcal{L} \mathrm{d}t < 10$ pb^{-1} of data is sufficient to discriminate between these models. ATLAS and CMS are both ready to study minimum bias and the underlying event at the LHC. Reconstructed distributions can be accurately corrected back to MC level. These analyses are an important first step in finding a model that describes the entire energy range up to the LHC.

Acknowledgments

References

1. T. Sjöstrand, S. Mrenna and P. Skands, *JHEP* **05**, 026 (2006).
2. R. Engel, PHOJET manual (program version 1.05c, June 96), http://www-ik1.fzk.de/~engel/phojet.html.
3. A. Moraes, C. Buttar and I. Dawson, *Eur. Phys. J.* C **50**, 435 (2007).
4. L. Evans et al., *JINST* **3**, S08001 (2008).
5. ATLAS Collaboration, G. Aad et al., *JINST* **3**, S08003 (2008).
6. CMS Collaboration, S. Chatrchyan et al., *JINST* **3**, S08004 (2008).
7. ATLAS Collaboration, G. Aad et al., "Expected Performance of the ATLAS Experiment, Detector, Trigger and Physics", arXiv:0901.0512.
8. R. Field, Talk presented at the Workshop on Advanced Monte-Carlo Use and Tuning at CMS, CERN, December 16, 2008.
9. CMS Collaboration, "Zero bias and HF-based minimum bias triggering for pp collisions at 14 TeV in CMS", CMS-PAS-QCD-07-002.
10. CMS Collaboration, "Pseudorapidity distributions of charged hadrons in minimum-bias p-p collisions at $\sqrt{s} = 14$ TeV", CMS-PAS-QCD-08-004.
11. F. Ambroglini et al., Proceedings of the Workshop on Monte Carlo's, Physics and Simulations at the LHC, arXiv:hep-ph/0902.0293.
12. CDF Collaboration, T. Affolder et al., *Phys. Rev.* D **65**, 092002 (2002).
13. CMS Collaboration, "Measurement of the Underlying Event in Jet Topologies using Charged Particle and Momentum Densities", CMS-PAS-QCD-07-003.